Surgical Techniques

3D Printing Protocol for Acute Intra-Articular Distal Radius Fractures: A Surgical Technique

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A three-dimensional understanding of fracture morphology improves anatomic reduction and internal fixation, improving care. Here, we describe our protocol for 3-dimensional (3D) printing acute distal radius fracture models for potential use in acute clinical care. We use our institutional 3D editing software (TeraRecon) to edit CT scans to exclusively include the distal radius and its pathology. Then, we use additional 3D editing software in Slicer 3D to convert DICOM files to STL files. Finally, using the Makerbot Replicator Z18 filament printer, we print individual models of distal radius fractures. This protocol will allow for the standardization of methods for 3D printing in acute scenarios, whereas there was no standardized protocol before.

INTRODUCTION

Understanding the biomechanical and anatomical concepts related to bone and fractures is essential to guide care.[1] Recently, 3-dimensional (3D) printing has been used to study these concepts and has been used for operative planning in specialties such as maxillofacial surgery, cardiovascular surgery, vascular neurosurgery, and others.[2] 3D printing technology further offers a novel modality by which fractures can be visualized and has been used to study fracture anatomy, specifically distal radius fractures.[3-5] These studies showed increased patient comprehension of fracture anatomy, increased surgeon confidence, decreased operative time, decreased blood loss, and decreased fluoroscopy time intraoperatively.[3-5] This manuscript aims to describe the technique for producing 3D fracture models for acute distal radius fractures (DRF) along with its feasibility regarding timing and cost to standardize 3D printing in the acute treatment of intra-articular distal radius fractures. To our knowledge, there are no current published protocols in the literature on the real-time printing of individual distal radius fractures. With this protocol, 3D printing in this setting can become standardized.

INDICATIONS AND CONTRAINDICATIONS

3D printing in our study was indicated for any acute complex distal radius fracture. These fracture patterns may include intra-articular involvement, comminution, and significant displacement. A complex distal radius fracture in our study was described as containing at least one of the following criteria: intra-articular step-off greater than 2mm, three or more fracture fragments, greater than 2mm displacement of fracture fragments, or intra-articular extension defined as a fracture line extending into the articular surface. There are no known contraindications.

TECHNICAL NOTE

Production of a 3D-printed acute DRF requires three basic steps: acquisition of a computed tomography (CT) scan, editing the file, and then 3D printing the file. For this project, we describe basic and advanced options for 3D printing acute DRF fractures utilizing Computer Aided Design (CAD) software.

I. 3D FILE ACQUISITION

1. Ideally, a CT scan with 2mm or less resolution of an acute DRF should be obtained.

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2. Download the CT images as a Digital Communications in Medicine (DICOM) file. This file type, considered a virtual 3D model, will be used to create a Standard Tessellation Language (STL) model for printing.

II. FILE EDITING

1. Utilizing Intuition TeraRecon, our institutionally available 3D editing software, the bone of interest can first be isolated in the DICOM file that is being edited. Keeping a wide window is important to better evaluate different anatomic structures. To isolate the bone of interest (distal radius and sometimes inclusive of distal ulna), manual subtraction of other bones can be utilized using tools similar to ("Free Reinforcement Orientation" or "Region" features). Next, rotate the model in the x, y, and z planes to best visualize the fracture site and orient the model to print to have the least interference with the fracture lines. This is how basic 3D DRF models were made from the DICOM file, which is then converted to an STL file using Slicer 3D in preparation for printing.

2. For more advanced prints with reduced artifacts (noise), our files were sent to our associated biovisual arts school (BVAS) at Rowan University to complete editing. The STL files are then refined and completed using virtual models utilizing Slicer 3D. This additional editing would reduce "artifacts" while orienting and optimizing the 3D files in preparation for printing. This file optimization requires additional labor but will reduce printed artifacts and extraneous supports.

> During the exporting of these files, smoothness and decimation are adjusted. The smoothness setting cleans the surface of the polygon mesh by iterative calculations. The decimate setting reduces the number of polygons in the final mesh. More decimation leads to a smaller file with less clarity but fewer calculations and a faster print. Smoothness and decimate settings were set to 50 and 75, respectively.

III. PRINT PREPARATION AND PRINTING

1. The STL file is next exported into the Makerbot software. The model requires orientation into the center of the build plate, rotating it to optimize support, fracture line placement, and surface area along the build plate. This should allow for increased model adhesion and decreased probability of the print warping on the build plate.

2. Address support structures in the Makerbot software to optimize time and material. Supports are necessary and automatically generated by printer-specific programs. They prevent model deformation, specifically for overhanging or bridging parts (slopes past 90 degrees and parts that connect the model at two points without underlying material, respectively). Supports, unfortunately, can decrease print fidelity at model interfaces due to residual material that can be left behind. To optimize these variables, we suggest the following:

   ◦ Set the overhang angle to 45-60 degrees.
   ◦ Orient the prints with minimal bridges and overhangs.
   ◦ Place fracture lines ideally either facing upward or perpendicular to the build plate to decrease support interfaces with those lines.

   Our prints were oriented with the lateral aspect of the radius along the build plate and the ulna perpendicular to the build plate. This increased the surface area along the build plate and minimized supports. The model density and exterior shell thickness may also be changed at this step.

3. Reaffirm optimal orientation, surface area, noise, scale, and supports, saving this within the final STL file.

4. Set the printer extruder and build plate temperature to the designated filament manufacturer's specifications. Export the model into a printer-specific file type for printing (i.e., MakerBot© file for MakerBot printers (New York, NY); Geometric Code (GCODE) file for other printers). This code processes the virtual 3D model into thin cross sections that the 3D printer can interpret to print a physical model layer by layer. The software will estimate the time and filament required for printing. It is essential to consider these parameters, which impact total material, cost, and time to print.

5. Load the printer with the appropriate materials. Our team used a Polylactic Acid (PLA) filament printer, the Makerbot Replicator Z18, a large, enclosed PLA filament 3D printer capable of printing detailed models up to 12 inches in width, 12 inches in depth, and 18 inches in height. It includes a heated build chamber and a heat-resistant build plate to ensure accurate printing without warping and other deformities. The printer settings were set to Makerbot's default settings. The print speed was set to 40 millimeters per second through a 4mm nozzle. The layers were set to a 0.16-millimeter height with 3 top layers, three bottom layers, and two shells. The first layer height was set to 90% and the width to 110%. The first layer speed was set to 50%. Infill was set to 10%, and the outline overlap was set to 40%. The print temperature was set to 215 degrees Celsius. Finally, we used a 0.25-millimeter z offset.

   ◦ The filament used was Makerbot PLA Material. Polylactic acid is a compostable and biodegradable polymer that is widely available and has diverse applications, including in orthopedic devices such as absorbable screws and pins that are utilized where low mechanical stiffness and strength are not required.[6] It contains various mechanical properties, ranging from soft and elastic to stiff and high strength, depending on how it is polymerized or blended.[7] In 3D printing, PLA filament is heated to become soft and
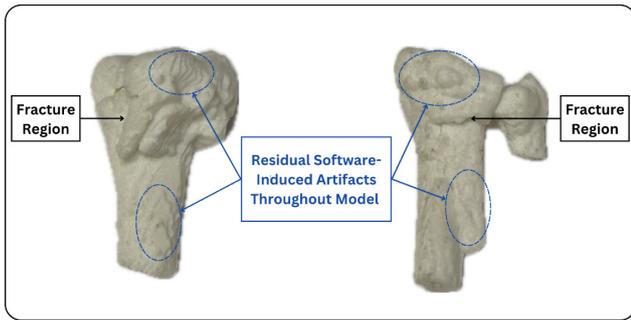
Figure 1. Examples of unprocessed 3D models showcasing collected distal radius fractures, where no alterations were made before fabricating the physical models. Take note of the visible software-induced artifacts across the model and fracture lines, imparting a cloudy and bumpy texture to the overall appearance.

Figure 2. Examples of additional distal radius fracture 3D models underwent supplementary post-processing via computer-aided design programs to remove software-induced artifacts. Observe the enhanced clarity of the model, characterized by a smoother radius bone stem and clearly defined fracture lines.

elastic, forming a model that condenses into a more solid, stiff, and mechanically strong model. Due to this property, PLA filament models are used to simulate bone properties in anatomic models more accurately.
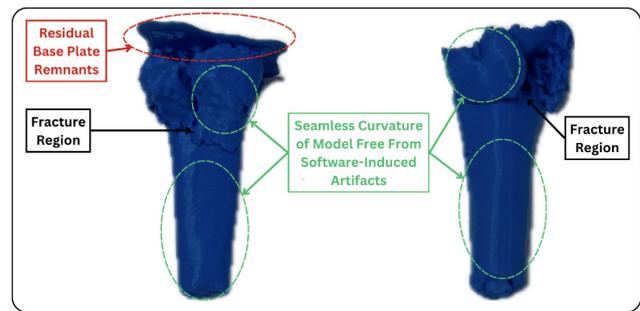
6. Start the print and observe it for appropriate build plate adhesion so that the print will be successful. Check the print at regular intervals if prolonged (>12 hours) to ensure no errors have occurred.

7. Once completed, remove support material from the model and discard it. We used a pair of flush wire cutters and precision tweezers. We suggest the following for removal:

   ◦ Gently grab the support with the wire cutters, then twist until the support breaks off the model at the interface.

   ◦ Remove any residual supports with the flush wire cutters or carefully remove them with precision tweezers.

The steps described above for 3D printing of DRF can be viewed in a peer-reviewed education video created by this study group.[8]

DISCUSSION

Our protocol produced 3D DRF models in as little as 2.5 hours (average: 220 minutes). The average production time for basic STL models was 166 minutes, including time for editing (30 minutes) and printing. The advanced STL files required 60 minutes for editing. Further, in these advanced STL models, a longer print time was necessary, increasing the average production time to 275 minutes. However, these advanced models had better fracture resolution. Both types of models are shown in the figures below. **[Figures 1 and 2]**

Production times vary due to several limitations. Production times are largely user-dependent and require an understanding of software and hardware, implying a learning curve influencing rapid printing. As experience im-

proves with this process, both editing and print times shorten. Further, the existence of various software and hardware options, as well as differences in access to printers, reduces external validity. Finally, model fidelity varies based on file type, print material, and 3D printer.

Model fidelity depends on several variables, many of which lie in the printer settings themselves, affecting how the model will print and, therefore, overall quality. First, the model's orientation dictates the filament arrangement in a PLA model, which can be likened to how bony lamellae dictate cortical structure. Orientation will also dictate the filament amount and support needed for the overall print to prevent deformation for the final 3D model. The wall thickness of the model may also be adjusted, and a delicate balance may be required. Thicker walls will allow for greater mechanical strength but will sacrifice print time and efficiency of filament use. A thicker model will, therefore, create a longer lag time from presentation to operation. Model infill can be adjusted as well. The model infill affects the overall density of the print, similar to how trabecular bone density changes with age and nutritional status. A higher infill creates a denser model, while a lower infill creates the opposite.

Alternative printing technologies, such as resin printers, are also available, but they have their own benefits and drawbacks. Resin tends to finish with higher quality and smoother surface finish than filament and may be able to print more complex models with higher fidelity. Resin models have also been shown to have greater tensile and flexural properties, but PLA models have been shown to have greater compressive performance.[9] However, resin printers may be more difficult for beginners, and the models take longer to cure and use more toxic materials. Each type of printing technology should be considered, as well as its own benefits and drawbacks. As filament is more readily available, easier to use and print, and less toxic, it was used for this study.

Further, post-processing enhancements such as smoothing had minimal effect on actual model accuracy but instead improved its quality. In this study, they were performed with consideration of normal anatomic structuring.

They were used to enhance anatomic landmarks prior to printing and reduce noise, increasing the quality of the overall print.

There are several start-up expenditures. Filament printers range in cost from below $200 to thousands of dollars. Our printer, the Makerbot Replicator Z18, costs $6500. The price difference may allow for different high-performance features, such as automation or better parts, for easier and more efficient model creation. PLA filament costs from $20 to $190 per roll. In filament, the more expensive rolls may have better adhesion and toughness. This is one of the most popular materials used in 3D printing, as it can be printed at a low temperature and typically does not require a heated build plate. We calculated that our models cost around $1-2 each - advanced models cost less to produce due to reduced material utilization. Other printers that use resin are associated with different costs, editing features, and print times. Resin printers were not used in this study. While we used editing software purchased through our institution, several premium and free editing options are available online. Often, different printing systems have their own software. Additionally, personnel that are familiar with 3D printing should be utilized. This incurs additional labor costs. Ideally, in-house professionals can be trained.

A recent study found that using 3D-printed models for assistance in DRFs decreased operative time, blood loss, and intraoperative fluoroscopy time without any outcome differences.[1] Further, two recent investigations showed that patients reported increased fracture comprehension and that surgeons experienced increased confidence using 3D printed models for DRF operative reductions, particularly in complex fracture patterns and preoperative planning of revision wrist surgery.[3,4]

Here, we add to the growing 3D printing literature with a protocol to 3D print DRFs to limit lead time as a barrier to 3D printing.[10] We note that even though there is a time barrier to printing, there are several advantages to printing these models that can improve care. There is a strong desire for protocol and education implementation in several surgical fields.[11-14] Therefore, future directions include developing curricula for medical trainees and enhancing the fidelity of the 3D model to quickly print products for practicing reduction, fixation, and biomechanical testing. **[Table 1]** Further, as a proof-of-concept study, this protocol is limited because it does not draw direct statistical comparisons between a control and experimental group. We further did not include a quantitative assessment of model quality, as to our knowledge, there is no standardized protocol or standard of assessment to which we can draw comparisons. These are valuable future directions to take in the implementation and standardization of 3D printing into clinical scenarios.

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DECLARATION OF CONFLICT OF INTEREST

DECLARATION OF FUNDING

DECLARATION OF ETHICAL APPROVAL FOR STUDY

This study was approved by our Institutional Review Board, approval number 22-069 on 4/25/2022.

DECLARATION OF INFORMED CONSENT

There is no information in the submitted manuscript that can be used to identify patients.

Table 1. Pearls and Pitfalls.

PEARLS	PITFALLS
• Enthusiasm for advancing surgical care through new technology will result in new frontiers for care • Learning 3D printing is a skill generalizable to many fields • The ability to work with several teams is key to successful printing and low production times	• Proper file formatting, editing, and setting optimization • Proper attention and preparation for model build plate adhesion • Initial cost of materials, software, and utilities • A substantial learning curve and team confidence in printing

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